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Evaluation of Corrosion Degradation Behavior of Aluminum Refrigerant Piping
for Air-Conditioning Systems

Seiji Uchiyama

Copper (Cu) is widely used for air-conditioning refrigerant piping in Japan owing to its workability and corrosion resistance. However, there is concern about the depletion of Cu resources due to the increased consumption by emerging countries and new technologies, such as electric vehicles. Cu prices have risen significantly in recent years, and the price of Cu is three times that of aluminum (Al). This doctoral dissertation focuses on Al, which is abundant and inexpensive, as an alternative material for refrigerant piping. To apply Al to air-conditioning refrigerant piping, this study demonstrates that Al refrigerant piping can perform as well as Cu refrigerant piping. This study comprehensively evaluates the performance of Al refrigerant piping over both short-term (approximately one year after the construction and completion of the building) and long-term periods (approximately 20 years, coinciding with the renewal of the air-conditioning equipment). In particular, this study analyzes the corrosion and degradation behavior of Al piping by examining the environmental and corrosive factors affecting both the interior (refrigerant passage) and the exterior (atmospheric exposure) of the piping, as well as piping manipulation conditions such as straight piping, bent piping, and piping covered with insulation. The dissertation is structured into six chapters, including an introduction and a conclusion.

In Chapter 1, the development history of CFC and other fluorocarbon refrigerants, regulatory trends on international environmental issues such as ozone depletion and global warming, trends in stock and pricing of raw materials used in refrigerant piping for air-conditioning, and the circumstances surrounding the construction industry and the demand for commercial air conditioners were reviewed. This was needed to organize the requirement for future air-conditioning refrigerant piping. As a result, it was clarified that future refrigerant piping needs to be installed using methods that improve workability in response to the decreasing number of construction workers, as well as functionality of traditional methods of air-conditioning equipment. Future refrigerant piping also needs to prevent leakage over long-term use to global warming concerns. Additionally, relevant regulations and standards, including the High-Pressure Gas Safety Act and related guidelines, for using Al in refrigerant piping were reviewed and summarized. The applicability of Al alloys and their pipe thickness for air-conditioning refrigerant piping was proposed, demonstrating that Al could be a realistic alternative to Cu for air-conditioning refrigerant piping.

In Chapter 2, we evaluated the short-term performance of Al for refrigerant piping, focusing on the constructability and operational performance of air-conditioning units. The thermal conductivity of Al

is $240 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, and the density of Al is $2.7 \text{ g}\cdot\text{cm}^{-3}$, while the thermal conductivity of Cu is $398 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, and the density of Cu is $8.9 \text{ g}\cdot\text{cm}^{-3}$. Although Al has a slightly lower heat dissipation capacity than Cu, it is significantly lighter. The tensile strength of Al is $105 \text{ N}\cdot\text{mm}^{-2}$, compared to $205 \text{ N}\cdot\text{mm}^{-2}$ for Cu. The wall thickness of refrigerant piping is generally designed by maintaining a constant outer diameter, considering the internal diameter of the insulating material and the tools used. According to regulations, Al piping requires a thicker wall than Cu piping. This affects constructability, especially bending, increasing internal resistance and potentially impacting air-conditioning performance. Experiments showed that using lightweight Al and specialized hydraulic tools improved constructability, reducing construction time by approximately 25% compared to Cu. Furthermore, the experiments clarified that pressure loss in the piping has a more significant impact on air-conditioning performance than the heat dissipation characteristics of the materials. Properly designed Al piping provided equivalent air-conditioning performance to traditional Cu piping. Thus, Al refrigerant piping not only reduces construction time but also maintains air-conditioning performance with appropriate design, demonstrating short-term performance similar to Cu piping.

In Chapter 3, We assumed the use of Al refrigerant piping for 20 years and analyzed the corrosion factors for both the inner (refrigerant flow area) and outer (exposed to the atmosphere) surfaces of the piping. We also conducted accelerated degradation tests for each factor.

The inner surfaces of refrigerant piping are exposed to fluorocarbon refrigerants and refrigeration oil. Under high temperatures, fluorocarbon refrigerants may gradually hydrolyze, producing acidic substances. Therefore, Al and Cu piping samples were immersed in a mixed solution of refrigerant and refrigeration oil and heated to the maximum practical operating temperature (120°C). Surface observations, weight measurements, and natural potential measurements were conducted before and after immersion. No significant changes were observed on the pipe surfaces after immersion, no significant weight loss was observed, and the natural potential of Al remained constant, suggesting that internal corrosion is unlikely within practical temperature ranges.

On the other hand, outer surfaces are exposed to chloride ions, water, and oxygen. Corrosion behavior and degradation of Al and Cu piping were evaluated by 496 hours of cyclic accelerated weathering tests composed of a cycle of salt spray (2 hours), drying (4 hours), and wetting (2 hours). The results showed that the initial corrosion products on Al piping function as a protective film, reducing further corrosion, and the weight loss owing to corrosion was less than that of Cu piping. Although pitting corrosion occurred, the depth of the pits stabilized over time and remained within the industrial allowance of 0.2 mm. The 62-cycle (496-hours) accelerated weathering test is equivalent to 1.5 years in Okinawa coastal areas and 20 years in inland areas like Kariya, Aichi. This evaluation demonstrated the practical usability of Al refrigerant piping in inland and indoor environments with minimal salt exposure.

In Chapter 4, we also focused on bent piping used in construction in addition to straight Al refrigerant piping. Bent piping was manipulated using a bender, and its electrochemical and mechanical properties, as well as weather resistance under tensile or compressive stress at each bend, were investigated. The purpose of this chapter was to experimentally verify the soundness of bent piping under conditions similar to those used in air-conditioning units. When pipes are bent using a mechanical bender, tensile stress occurs on the outer side of the bending curve, and compressive stress occurs on the inner side. In corrosive environments, stress corrosion cracking (SCC) can be induced in Al alloys by the breakdown of the protective oxide film under tensile stress. To understand the mechanical properties, tensile tests were conducted at three different speeds ($1 \text{ mm} \cdot \text{min}^{-1}$, $10 \text{ mm} \cdot \text{min}^{-1}$, $100 \text{ mm} \cdot \text{min}^{-1}$), revealing no significant differences in nominal stress and nominal strain, confirming that these speeds are within the range of practical strain rates. Using these results, finite element analysis showed that Al and Cu pipes exhibited similar strain values, indicating that Al demonstrates mechanical properties comparable to Cu within practical bending ranges. Electrochemical properties were evaluated by measuring the natural potential of bent pipes immersed in a $30 \text{ }^{\circ}\text{C}$, $3.0 \text{ mol} \cdot \text{L}^{-1}$ NaCl solution using a three-electrode method. The results indicated that the tensile side of the bent Al piping showed greater deviations in natural potential with increasing curvature, suggesting slight oxidation progression. Accelerated weathering tests for 496 hours (equivalent to 1.5 years in coastal Okinawa or 20 years in inland Kariya, Aichi) showed no significant differences between bent and straight sections in terms of base material integrity. SEM-EDX observations and LIBS analysis revealed that Cu pipes had Cu_2O and CuCl deposits on the surface, while Al pipes formed Al_2O_3 . Despite some pitting corrosion on the Al tensile side, the protective oxide layer reformed during wetting and drying cycles, minimizing surface damage. These findings confirm that Al refrigerant piping bent using mechanical benders are practical for use, maintaining performance comparable to straight sections and Cu piping.

In Chapter 5, we investigated the corrosion degradation behavior of Al and Cu piping with thermal insulation covering. To simulate potential damage from corrosion under insulation (CUI), pipes covered with thermal insulation were immersed in a NaCl solution. The polyethylene foam insulation absorbed a significant amount of the solution, leading to pronounced surface corrosion on both Al and Cu piping. However, SEM analysis revealed that the corrosion products formed a protective film on the pipe surfaces, maintaining the integrity of the base material of both Al and Cu. These results suggest that Al piping can be utilized under thermal insulation in environments with a pH of approximately 6 to 7. However, understanding the corrosion degradation behavior in environments outside this pH range remains a future challenge.

In Chapter 6, the application of Al piping as a replacement for Cu in air-conditioning systems is summarized. Replacing Cu with Al piping offers advantages in terms of workability and cost-

effectiveness. This doctoral dissertation found that Al piping demonstrates sufficient durability in environments that involve cycles of wetting and drying at neutral pH, as the corrosion products formed in these conditions act as a protective film, maintaining the integrity of the base material. Al piping can be used in many practical environments. However, understanding the corrosion degradation behavior in environments where Al is prone to ionization or where Cu or iron (Fe) are present remains a future challenge.